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SPACING ANALYSIS OF AN INCLINED SOLAR COLLECTOR FIELD

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ABSTRACT

Spacing between the adjacent collectors in a solar field is an important parameter which effects the shading and hence the energy conversion from collectors. Land value has an important bearing on the spacing between the collectors. A computer code has been developed to predict the change in incident energy on the collectors for various spacing distances between them. The code couples general shading models with the local weather data (TMY2). This can be used to calculate shadow area on the collectors from their adjacent collectors for different times of the day for various spacing distances. Variation of shadow area of the collectors for various spacing distances is presented for various time periods. It has been observed that near sunrise and sunset the percent shading area of a system is generally higher, but its influence on the overall energy collection is relatively less due to the decreased solar insolation available during those times of the day. The variation of annual energy received for various spacing distances is presented. Results are given for locations in the Southwestern region of the US including Las Vegas, Phoenix and Albuquerque. Economic implications of these results are discussed.

Keywords: shading, solar field, field layout, solar collectors, shading algorithm

1. INTRODUCTION

There has been a steady increase in the global energy demand. Excessive use of fossil fuels to meet this demand has raised concern over environmental effects. Renewable energy sources such as solar and wind can be sustainable alternatives to reduce the dependence on conventional fuels. There has been an increased interest

in solar energy over the past few years. Many solar power plants are currently being built and many others are under consideration throughout the world. In large solar installations consisting of many collectors, it becomes possible for the shadow of one collector reduce solar radiation to adjacent units.

For this reason, shading considerations must be taken into account prior to construction of the facility. Hence, mathematical models, which can predict the variation of the shadow for various times of a day and seasons of a year considering the effects of various parameters in a field of collectors, were developed by many researchers [1-6]. In a field of solar collectors, shading is highly dependent on the spacing between the collectors in addition to the other parameters such as orientation and location of the collectors. Mathematical models to calculate the shading effect for various tracking type of collectors were reported [3]. These models can be used to predict the optimal spacing between the collectors. Optimization models to calculate the maximize the energy and minimize the area of solar fields of collectors were also reported [6]. These studies point to the importance of collector spacing as an important parameter when developing the layout for a system. For fixed collectors, spacing in the east-west direction (which corresponds to the length of collectors for a given width of the field) is of lesser importance when compared to the spacing distance in the north-south direction. As was shown by Appelbaum and Bany, shaded area is independent of collector length for units longer than 25 m in the east-west direction [1]. The spacing distance in the results refers to the spacing in the north-south direction.

In the design of solar power plants it is generally required to maximize the annual yield. In the present

study a computing code to perform the parametric study of shadow area and total year-round energy received was performed and the results are presented for three locations in the desert south-west. The code uses the weather data TMY2 [10] for different locations.

2. MATHEMATICAL MODELING

Solar collectors fixed in the field as s assumed as shown in Fig. 1, in the development of mathematical models. As can be seen from the figure the collectors are tilted at an angle β facing due south. The dimension of the collectors in the east-west direction is referred as length, L and the dimension A is referred to as width.

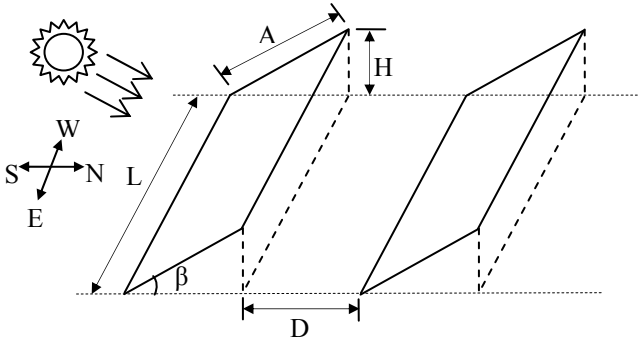


Fig. 1. Schematic of fixed inclined solar collectors

The distance between two consecutive collectors in the north-south direction is referred to as the spacing distance, D. The mathematical models developed in this study are based on the models developed by Appelbaum and Bany [1]. The following are the equations used in the development of algorithm.

Hour angle (ω) in degrees is calculated as

$$\omega = -(12 - \text{solar time}) \cdot 15$$

Standard procedures as presented in Duffie and Beckman are followed in the calculation of solar time.

Angle of Incidence (θ) is shown as [9]

$$\begin{aligned} \cos \theta = & \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma \\ & + \cos \delta \cos \phi \cos \beta \cos \omega + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega \\ & + \cos \delta \sin \beta \sin \gamma \sin \omega \end{aligned}$$

Yearly energy received by an unshaded collector is given as

$$Q_{unshadyearly} = AL \cdot \left[\sum_i I_{bi} \cdot \cos \theta_i + I_{di} \cdot \cos^2 \beta / 2 \right]$$

where i is hour, 1...8760

Relative Shaded Area (ξ) is calculated as [1]

$$\xi = \left[1 - \frac{\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta}{\cos(\phi - \beta) \cos \delta \cos \omega + \sin(\phi - \beta) \sin \delta} \cdot (d \sin \beta + \cos \beta) \right] \cdot \left[1 - \frac{\cos \delta \sin \omega \sin \beta}{\cos(\phi - \beta) \cos \delta \cos \omega + \sin(\phi - \beta) \sin \delta} \cdot \left(\frac{d + \cot \beta}{l} \right) \right]$$

where $l = \frac{L}{H}$, $d = \frac{D}{H}$ and $H = A \sin \beta$

Screening Angle (η) [1]

$$\eta = \frac{1}{A} \int_0^A \arctan \left[\frac{(A-x) \sin \beta}{D+x \cos \beta} \right] dx$$

The yearly solar energy received by a shaded collector considering the shadow and screening effects of neighboring collectors on beam and diffuse radiations is [1]

$$Q_{shad, yearly} = AL \cdot \left[\sum_i (1 - \xi_i) I_{bi} \cos \theta_i + I_{di} [(\cos^2 \beta / 2 + \cos^2 \eta / 2) - 1] \right]$$

where i is hour, 1...8760

3. DEVELOPMENT OF SHADING ALGORITHM

A computing code was developed using MATLAB for shadow analysis for fixed collectors in a solar field. The code allows the shading models to be coupled to the local weather data (TMY2). The algorithm is useful for the prediction of the following:

- relative shaded area for various times of a day for various spacing distances,
- the total energy received in a year by shaded collectors for different spacing distances, and
- change in the year-round received energy of collectors for various tilt angles etc.

As was mentioned previously, the collectors are assumed to be installed as shown in the Fig. 1. The model assumes that the solar field will be made up of two types of collectors. The first type is an unshaded front collector. This would be first row of collectors on the south edge of the array. The second type is a shaded rear collector. This consists of all of the collectors not included in the first group. To compare how shading affects the energy received by the collector, the simulation results are presented for these two types. These results can be easily extended to calculate the total energy incident in a field of collectors by finding the number of shaded and unshaded collectors in the field.

4. OPTIMUM TILT ANGLE OF COLLECTORS

For fixed collectors the energy received depends on the tilt angle (β) as shown in Fig.1. It is a widely accepted rule of thumb to install the fixed collectors at a tilt angle equal to the local latitude to maximize yearly yield. To verify this general idea the developed code was used for the three southwest locations of the US. The year-round total energy received for various tilt angle collectors considering the shadow effects in a solar field is shown in Fig. 2. As can be seen from the figure, the maximum energy is received at tilt angles approximately 5° less than the local latitude. The variation of year-round energy received for tilt angles in the range between latitude-15 to latitude is less than 50 kWh/m^2 (<3%). A significant energy loss can be observed for tilt angle beyond the latitude. These results are based on the TMY2 data. Similar observations were reported by other researchers [8].

5. RESULTS AND DISCUSSION

Simulation results for three southwest locations in the US viz. Las Vegas, NV, (latitude = 36.08°N , longitude = 115.17°W , local meridian = 120°W) Phoenix, AZ, (Latitude = 33.26°N , longitude = 112.02°W , local meridian = 105°W) Albuquerque, NM, (latitude = 35.05°N , longitude = 106.64°W , local meridian = 105°W) are presented. The following results are based on the assumptions that the collectors are fixed at an angle equal to the local latitude and facing due south. The results presented are for solar collectors of length, $L = 10 \text{ m}$ and width, $A = 2 \text{ m}$ and tilt angle $\beta =$ latitude of the location.

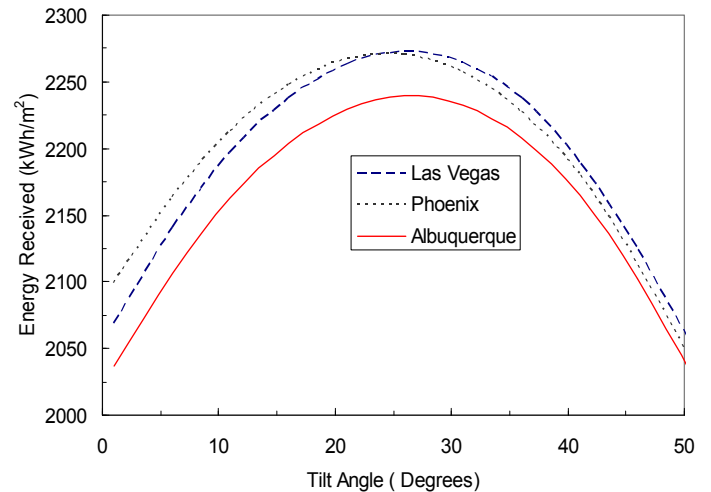


Fig. 2. Variation of energy received with the tilt angle of collectors

5.1. Shadow area on collectors

In a solar field, depending on the position of the sun in the sky, the shaded area on collectors (due to neighboring collectors) varies over time for a given spacing distance and size of collectors. At any location, for a given dimensions of the collectors, spacing distance the shadow area is maximum during the winter. Hence, the variation of relative shaded area over time for different spacing distances for the three locations for a winter day is shown in Figs. 3, 4 and 5. The variation of beam radiation for the corresponding days is also shown in the figures. It can be observed that, for a smaller spacing distance between collectors the shadow area increases. As shown in Fig.3, for Las Vegas, decreasing the spacing below 2.0 m would result in the shading of collectors throughout the day. Similar observations can be made for other locations. From Figs. 3, 4 and 5, it can also be observed that the shadow area is minimum at noon and increases towards the early and late hours in a day. Due to the fact that the solar insolation generally peaks around noon the effect of shadow during the early and late hours has less influence on the total energy received by the collectors. As can be seen from Figs. 3, 4 and 5, the area between the solar insolation and shadow curves is the energy received, which is higher for larger spacing curves. The peaks on the shading curves during the early morning and late afternoon hours are caused by the reduced shadow width during these times.

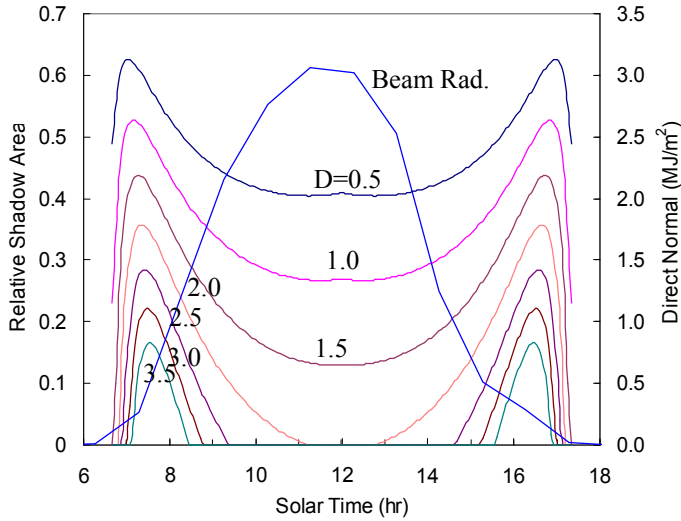


Fig. 3. Variation of shaded area and solar radiation over time for January 1 for Las Vegas, NV

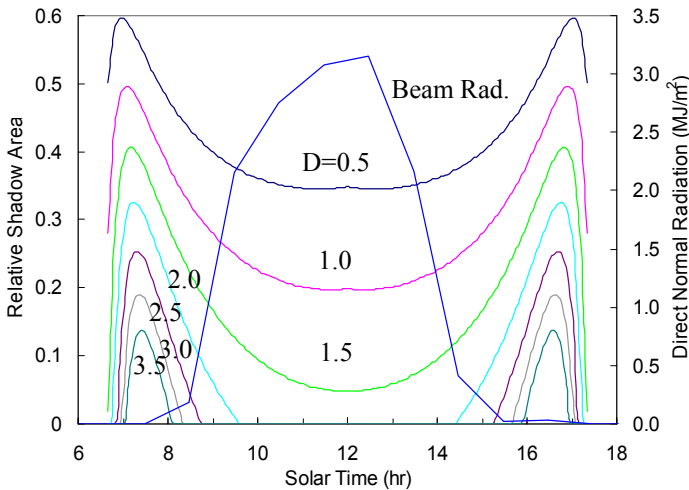


Fig. 4. Variation of shaded area and solar radiation over time for January 1, for Phoenix, AZ

5.2. Effect of shadow area

The energy conversion from collectors is not always scalable based on shaded area alone. It depends on the conversion process being utilized. In a thermal collector the converted energy is proportional to the shaded area, whereas in PV systems the effect of shading is more pronounced depending on the electrical connection between the cells and the modules. In a solar field, it is practically impossible to completely avoid shading on the collectors. Hence, insights into the shading area for various times of the day and year would be useful in the

design of the electrical circuitry between the modules in case of PV systems. As can be seen from Figs. 3, 4 and 5 the relative shaded area is always less than 60% for collectors that are spaced down to 0.5 m.

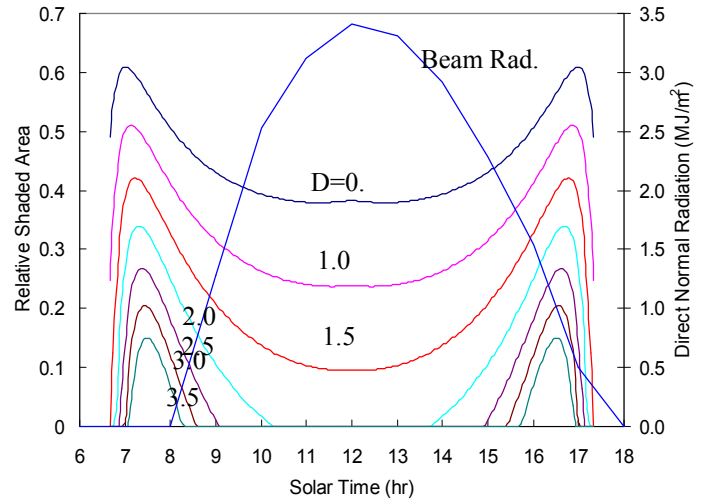


Fig. 5. Variation of shaded area and solar radiation over time for January 3 for Albuquerque, NM

5.3. Year-round energy received

The variation of year-round energy received with spacing distance for different widths (A) of the collectors for the three locations is shown in Figs. 6, 7 and 8. The straight lines in the figures represent the year-round energy receive-

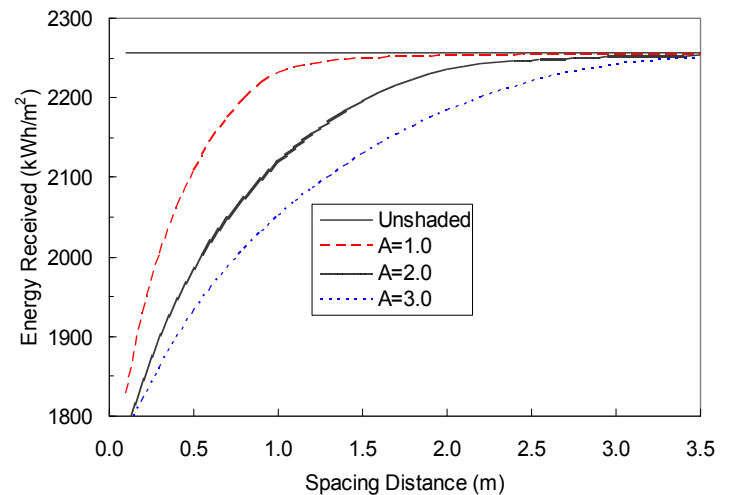


Fig. 6. Variation of received annual energy with spacing distance for Las Vegas, NV

ed by an unshaded collector. The curved lines represent the energy collected by shaded collectors for different heights. As can be seen from the figures, the total year-round energy received by an unshaded collector is

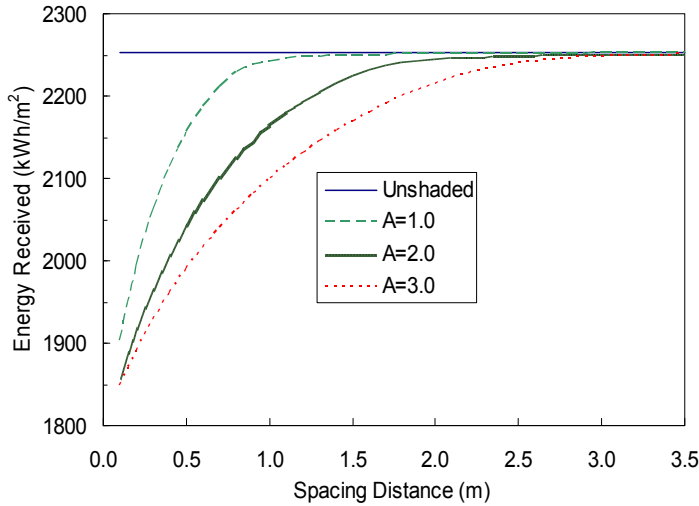


Fig. 7. Variation of received annual energy with spacing distance for Phoenix, AZ

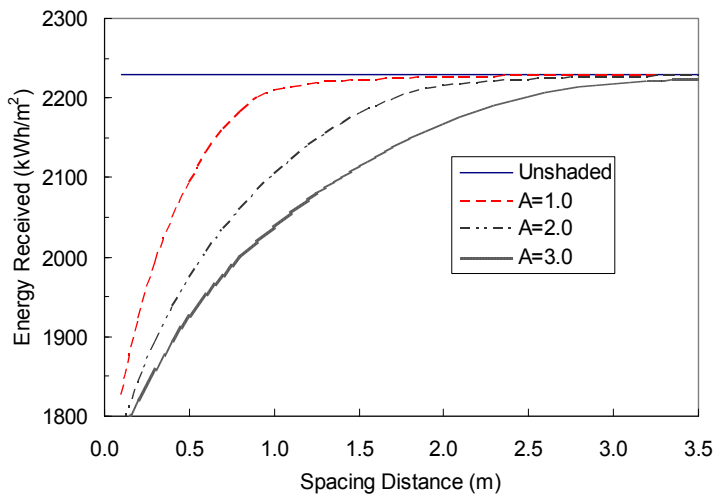


Fig. 8. Variation of received annual energy with spacing distance for Albuquerque, NM

~2250 kWh/m² for the three locations, and the shaded collectors approached this value as the spacing increased. However, the energy gains are negligible beyond the spacing distances approximately 1, 2 and 3 m for collector widths 1, 2 and 3 respectively, for Las Vegas as shown in Fig. 6. Almost similar trends are noted for the other two locations as shown in Fig. 7 and Fig. 8, because all the three locations geographically close.

These results can be extended to find an optimal spacing provided the land and energy pricing.

6. SUMMARY AND CONCLUSIONS

A MATLAB code which coupled the mathematical models of the shadow analysis with TMY2 data is developed. The simulations for the optimum tilt angle demonstrates that the maximum year-round energy can be achieved at a tilt angle 5° less than the latitude of the location. Shadow area is minimum at noon and increases towards the early and late hours in a day. The solar insolation, however, peaks around midday and decreases towards the early and late hours of the day. Hence the effect of shadow area during the early and late hours has less influence on the total energy received by the collectors. The annual energy received by shaded collectors approaches the unshaded case as the spacing between the collectors increased. However, the energy gains are negligible beyond the spacing distances approximately 1, 2 and 3 m for collector widths 1, 2 and 3 respectively, for Las Vegas. Almost similar trends are noted for the other two locations, because all the three locations geographically close. The developed code will be extended for further investigations on field optimization by including the economic aspects such as land and energy pricing.

NOMENCLATURE

- A collector width
- D north-south spacing between collectors
- d D/H
- I_b beam insolation (Wh/m²)
- I_d diffuse insolation (Wh/m²)
- H height ($H = A \sin \beta$) (meters)
- L collector length (meters)
- l L/H
- Q annual energy received (kWh)
- β tilt angle of the collectors
- θ angle between surface normal and solar ray
- ϕ local latitude
- γ solar azimuth
- δ solar declination angle
- ξ relative shaded area
- η screening angle
- ω solar hour angle

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